Paper

THE USE OF COMPARATIVE ^{137}Cs BODY BURDEN ESTIMATES FROM ENVIRONMENTAL DATA/MODELS AND WHOLE BODY COUNTING TO EVALUATE DIET MODELS FOR THE INGESTION PATHWAY

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***Abstract*—Rongelap and Utirik Atolls were contaminated on 1 March 1954, by a U.S. nuclear test at Bikini Atoll code named BRAVO. The people at both atolls were removed from their atolls in the first few days after the detonation and were returned to their atolls at different times. Detailed studies have been carried out over the years by Lawrence Livermore National Laboratory (LLNL) to determine the radiological conditions at the atolls and estimate the doses to the populations. The contribution of each exposure pathway and radionuclide have been evaluated. All dose assessments show that the major potential contribution to the estimated dose is ^{137}Cs uptake via the terrestrial food chain. Brookhaven National Laboratory (BNL) has carried out an extensive whole body counting program at both atolls over several years to directly measure the ^{137}Cs body burden. Here we compare the estimates of the body burdens from the LLNL environmental method with body burdens measured by the BNL whole body counting method. The combination of the results from both methods is used to evaluate proposed diet models to establish more realistic dose assessments. Very good agreement is achieved between the two methods with a diet model that includes both local and imported foods. Other diet models greatly overestimate the body burdens (i.e., dose) observed by whole body counting. The upper 95% confidence limit of interindividual variability around the population mean value based on the environmental method is similar to that calculated from direct measurement by whole body counting. Moreover, the uncertainty in the population mean value based on the environmental method is in very good agreement with the whole body counting data. This provides additional confidence in extrapolating the estimated doses calculated by the environmental method to other islands and atolls.**
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Key words: Marshall Islands; ^{137}Cs; dose; diet

INTRODUCTION

RONGELAP AND Utirik Atolls were contaminated on 1 March 1954, by a U.S. nuclear test at Bikini Atoll code named BRAVO. The location of the atolls in the Marshall Islands is shown in Fig. 1. A photo montage of each atoll is shown in Figs. 2 and 3. The people living on Rongelap at the time of the BRAVO test were removed from the atoll by the U.S. military about 48 h after the start of the fallout. The Rongelap community was returned to their atoll in June of 1957, and the people resided on Rongelap until May 1985 when they decided to move to an island in the northern part of Kwajalein Atoll. Resettlement plans for Rongelap Island are currently being developed, and are based in large part on dose estimates to the returning population that are based on measured radionuclide concentrations in the soil and vegetation on the island, and dose models that include estimates of intake of locally grown foods (Robison et al. 1994). The Utirik people were also relocated in the first few days after the BRAVO test, and they were returned to their atoll about 3 mo later and continue to reside there today. Their resettlement occurred more rapidly because the dose at Utirik was much lower than at Rongelap.

The exposure pathways at the contaminated atolls are external gamma, inhalation, and ingestion. The potential uptake through a wound is so minor that it is not included. The ingestion pathway includes intake of terrestrial foods, marine foods, and cistern and groundwater. Extensive work has been done since the mid 1970's by LLNL to document the radiological conditions at Bikini, Enewetak, Rongelap and Utirik Atolls to provide dose assessments for alternate living patterns for people wishing to resettle their islands. Detailed studies have been carried out to evaluate the contribution of each exposure pathway. These studies show that the radionuclides remaining today that contribute in any significant way to the estimated dose are ^{137}Cs ^{90}Sr, $^{239+240}Pu$, and ^{241}Am.

All the dose assessments for the various atolls show that the major potential contribution to the estimated dose is ^{137}Cs uptake into terrestrial foods, and the subsequent consumption of these foods by the people.

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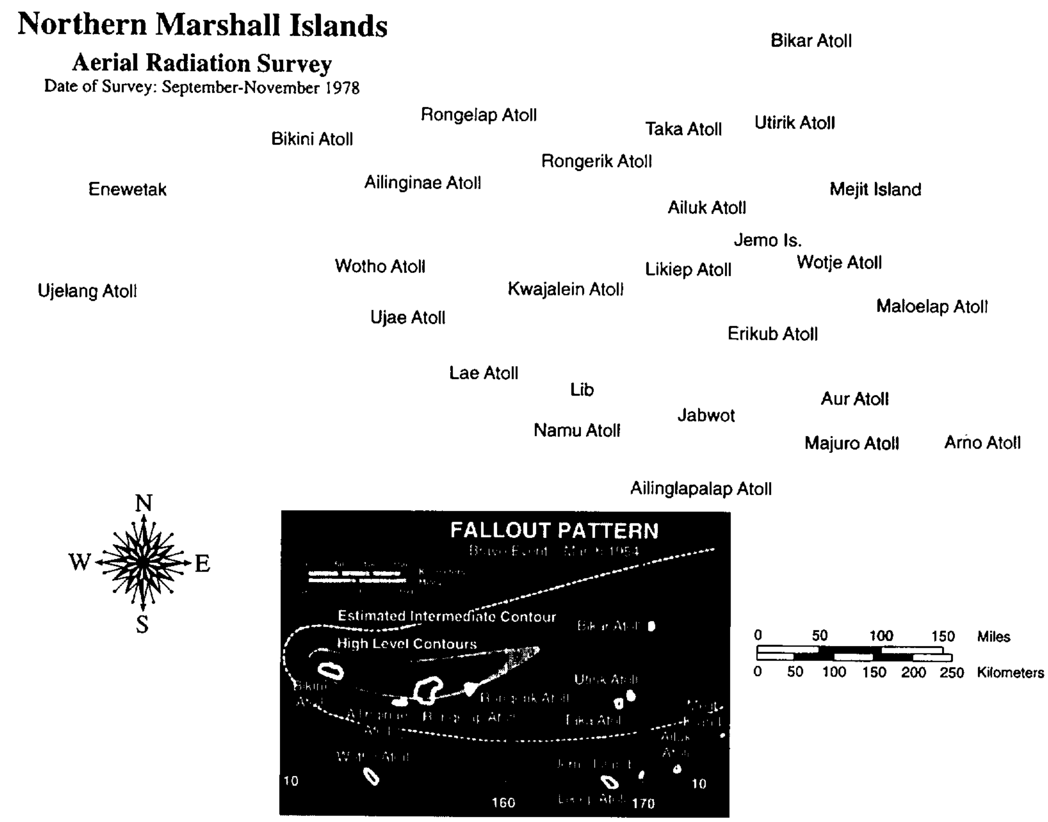

Fig. 1. A photographic montage of the Marshall Islands showing the location of Rongelap and Utirik Atolls.

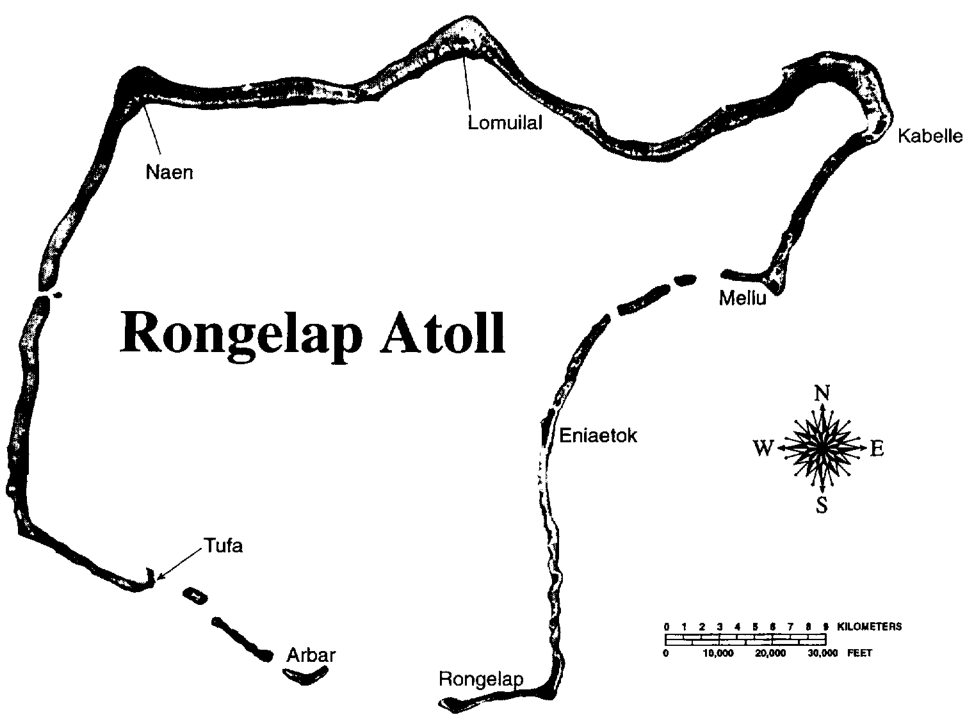

Fig. 2. A photographic montage of Rongelap Atoll showing the location of Rongelap Island which is the main residence island.

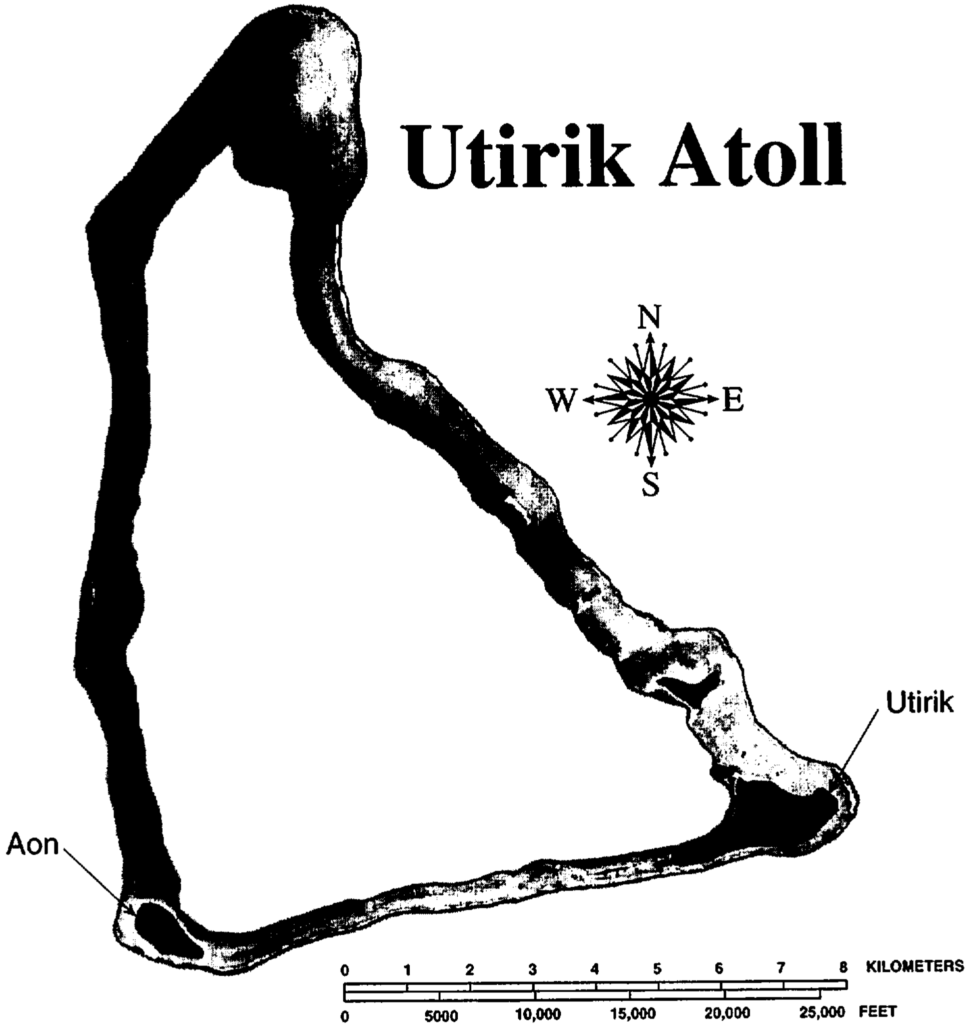

Fig. 3. A photographic montage of Utirik Atoll showing the location of Utirik Island which is the main residence island.

^{137}Cs in the terrestrial food chain accounts for about 90% of the dose at the atolls (Robison et al. 1997).

The Brookhaven National Laboratory (BNL) between 1970 and 1984, has performed many whole body counting field missions to monitor the ^{137}Cs body burdens of the Rongelap and Utirik people while they were living on their respective islands (Greenhouse et al. 1977; Miltenberger et al. 1981; Lessard et al. 1980a, 1984). These whole-body count data provide a direct measure of the ^{137}Cs body burdens for comparison with predicted body burdens based on the environmental data and models. BNL's program also included whole body measurements of the Bikini people who resettled Bikini between 1970 and 1978, and the Enewetak community after their return to the southern half of Enewetak Atoll in 1980 (Lessard et al. 1980b; Miltenberger et al. 1980; Greenhouse et al. 1980).

Before 1985, the Rongelap population lived primarily on Rongelap Island, which is a narrow island about 120 ha in size (Fig. 4), and consumed local foods from the island. Some coconut and *Pandanus* were collected from Arbar Island next to Rongelap Island, and some people lived on Arbar for extended periods of time; however, this does not change the dose estimates because the radionuclide concentration in the soil and vegetation are the same as on Rongelap Island (Robison and Conrado 1996). The relatively small island area, well defined by bordering ocean and lagoon, makes it possible to thoroughly determine the radionuclide concentration in local food crops and the associated ranges and distributions. It was also possible to access the adult population so that many adults were analyzed by BNL by whole body ^{137}Cs measurements over a period of several years. The situation at Utirik Atoll is very similar, although the main residence island is somewhat smaller (Fig. 5).

Another important feature of both Rongelap and Utirik is that the populations resided on their islands continually (with, of course, occasional trips off-island) from 1957 through May of 1985 for Rongelap, and June of 1954 to the present day for Utirik, so that a steady state

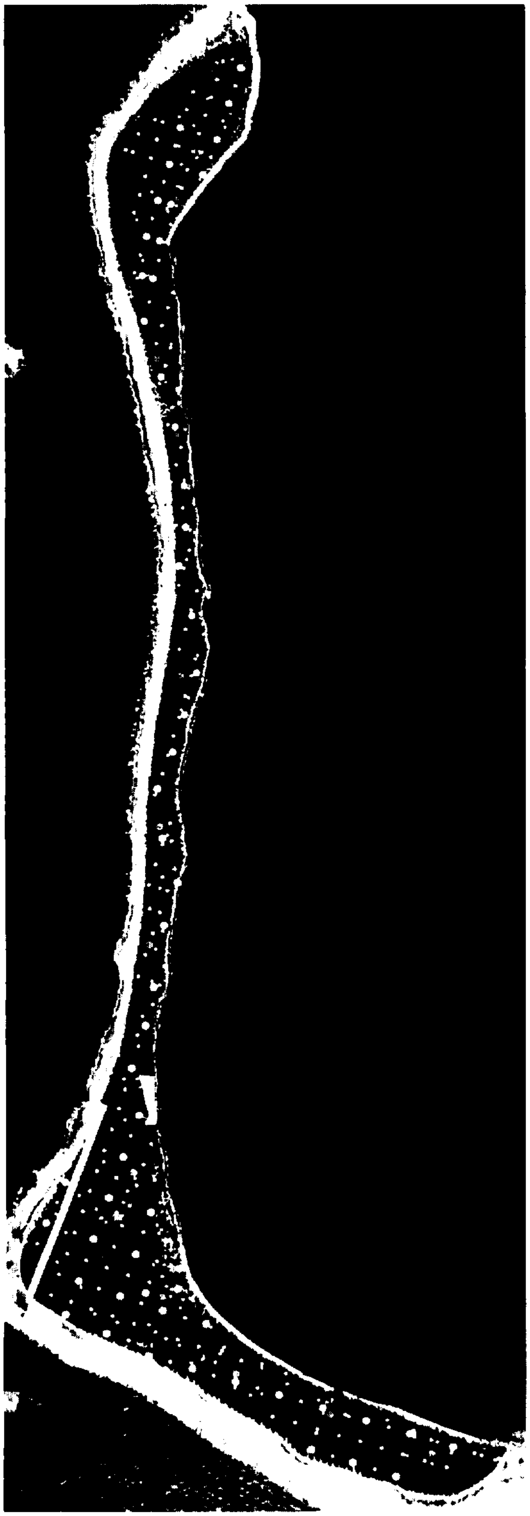

Fig. 4. An aerial photograph of Rongelap Island with soil, vegetation, and gamma spectrometry sampling sites superimposed.

condition existed for the ^{137}Cs body burdens averaged over time periods of a year. Seasonal variations in the dietary intake of local foods can and do occur due to the seasonal production of breadfruit and *Pandanus* fruit.

The average annual body burden estimated from the environmental data and models (hereafter referred to as the "environmental method") are based on the measured concentrations of radionuclides in foods (Robison et al. 1994, 1997), the average dietary intake of the various local foods (Robison et al. 1994, 1997), and the ^{137}Cs dose model (Leggett 1986; ICRP 1979, 1990, 1991). BNL whole body measurements of the adult population were made annually (occasionally biannually), and at different times of the year so that over a period of time any seasonal dependence would be averaged out. Moreover, some variations would be expected in the BNL average population body burden from year to year because the same people at each atoll were not always measured every year; each year the population group analyzed was essentially a random sample dictated by who volunteered to be measured on a given trip.

The dietary intake of local foods is a very important part of the LLNL environmental method used to generate the estimated body burdens and dose. Unfortunately, the exact dietary intake of local foods often is not well known. When it is not well known, various diet models are proposed, and sometimes insisted upon, by people, groups, or government agencies that lead to radionuclide intakes that can range over an order of magnitude.

In this paper we compare the estimates of the body burdens at Rongelap and Utirik Atolls from the LLNL environmental method with the body burdens measured by the BNL whole body counting method. The data base for the radionuclide concentrations in local foods is very extensive (Robison et al. 1994); also, the biokinetic model for ^{137}Cs uptake, transport, and distribution in the human body is well documented (Leggett 1986; ICRP 1979, 1990). Consequently, we can, in conjunction with the whole body measurements, demonstrate the usefulness of the environmental method to help define realistic dietary intakes of locally contaminated food at the northern atolls of the Republic of the Marshall Islands that are crucial to realistic dose assessments.

METHODS

Environmental data and dietary models

Samples of soil, vegetation (food crops and natural species), marine species, animals, fowl, and ground and cistern water were collected at the atolls, frozen aboard ship, and returned to LLNL for processing. Each individual sample was double bagged and sealed to prevent any contamination from other samples. Water samples were collected in individual 5- or 15-gallon containers for shipment to the laboratory.

Vegetation, food crops, animal, fish and other marine species, and fowl samples were freeze dried upon return to the laboratory and subsequently ground to uniform consistency and packed in steel tuna cans 8 cm in diameter and 4.0 cm in depth for gamma spectroscopy. Additional aliquots of the sample were sometimes sent for radiochemistry analysis of ^{90}Sr, $^{239+240}$Pu, and ^{241}Am. Some samples were ashed prior to chemical

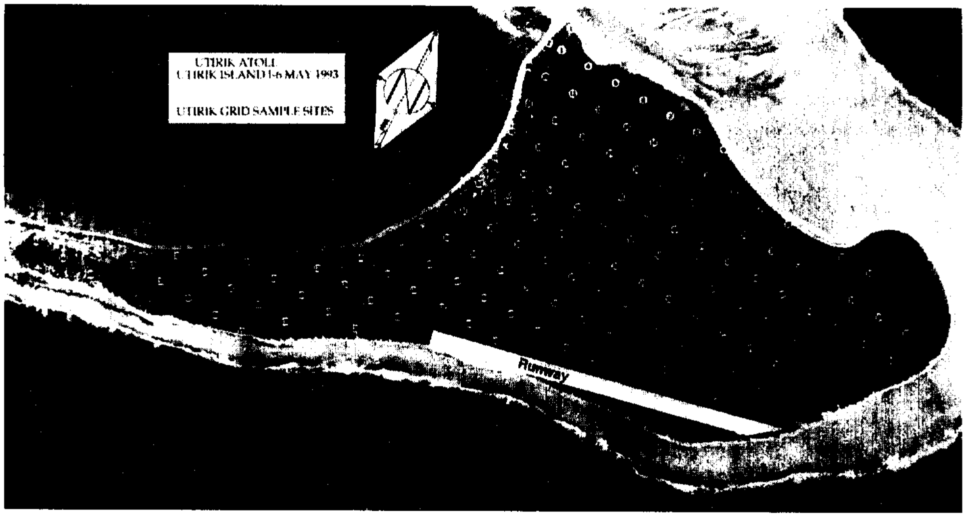

Fig. 5. An aerial photograph of Utirik Island with soil, vegetation, and gamma spectrometry sampling sites superimposed.

separation in preparation for wet chemistry analysis (Wong et al. 1994). The LLNL radiochemistry facility has a multitude of analytical equipment that includes alpha spectrometers with surface barrier detectors for analyzing $^{239+240}$Pu, ^{238}Pu, and ^{241}Am, and beta spectrometers for ^{90}Sr analysis. A summary of our radiochemistry procedures for processing samples, separating radionuclides, and analyzing for several radionuclides and elements is available in a recently updated report (Wong et al. 1994).

Soil samples were oven dried to constant weight, ball milled to a fine talcum powder consistency and canned for gamma spectroscopy in the same geometry as the vegetation samples. Again, aliquots were sometimes sent for radiochemistry analysis. Sample processing of soil for wet chemistry radionuclide analysis is described in Wong et al. (1994).

The LLNL gamma-spectroscopy facility consists of 22 high-resolution, solid-state gamma detectors with associated electronics. Details of the facility design, internal calibration procedures, and general operation can be found in recent updated reports (Brunk 1995a, b).

Both the gamma-spectroscopy and radiochemistry facilities have their own "internal" quality control procedures (Wong et al. 1994; Brunk 1995a, 1995b) and an extensive "external" quality control program that has been in place for years. Standard and duplicate samples that are blind to the analysts are submitted with each group of 50 samples submitted to either our own facilities or an outside contractor. The LLNL acceptance protocols are as follows: (1) the standard samples must be within 10% of the known value or the entire set of samples is rejected and must be reanalyzed; and (2) the duplicate samples must also be within 10% of each other for most samples; the error allowed does increase as the total activity in the samples decreases, especially for $^{239+240}$Pu and ^{241}Am analyses (Kehl et al. 1995).

Additional quality assurance is provided through multiple intercalibration exercises every year with the International Atomic Energy Agency (IAEA), National Institute on Standards and Technology (NIST), and other organizations. The IAEA intercalibration exercises cross-calibrate the LLNL analytical results with other participating laboratories around the world. Another important part of our quality control program is the use of "split samples" with other laboratories. For example, in many cases the soil and vegetation samples are collected by LLNL and other participants, split in the field, and subsequently analyzed by both parties. In other cases the samples are homogenized in the laboratory then split and sent to us from other laboratories, or sent by us to other labs, for analysis. A recent updated report details our quality control procedures and results (Kehl et al. 1995).

The estimated average intake of local and imported foods used in the dose assessment is a very important parameter; radiological dose (or body burden) will scale directly with the total intake of ^{137}Cs, which is proportional to the quantity of locally grown foods that are consumed. Therefore, a reasonable estimate of the average daily consumption rate of each food item is essential. LLNL and its independent committees, in concert with local government authorities, with the legal representatives of the people, with Peace Corps representatives, and anthropologists have endeavored to establish and document pertinent trends, cultural influences, and economic realities—with the hope that the estimates of intake rates for local foods are objective and realistic.

The LLNL preferred diet model, the so called "imported food available" (IA) diet model, used to estimate the dose from ^{137}Cs at the atolls is listed in Table 1 for Rongelap Island and includes consumption of both local and imported foods. A diet consisting entirely of consumption of local foods, "imports unavailable" diet (IUA), for Rongelap Island is listed in Table 2. The diet

Table 1. Diet model—Rongelap Island. Local and imported foods available for adults greater than 18 y.

				Specific activity in 1995 (Bq g^{-1} wet wt.)				Bq d^{-1}			
Local food	g d^{-1}	kcal g^{-1}[a,b]	kcal d^{-1}	^{137}Cs	^{90}Sr	$^{239+240}Pu$	^{241}Am	^{137}Cs	^{90}Sr	$^{239+240}Pu$	^{241}Am
Reef fish[d]	24.2	1.40	33.8	6.7×10^{-4}	2.4×10^{-5}	1.2×10^{-5}	1.4×10^{-6}	1.6×10^{-2}	5.9×10^{-4}	3.0×10^{-4}	3.3×10^{-5}
Tuna	13.9	1.40	19.4	6.0×10^{-4}[d]	2.4×10^{-5}[e]	3.0×10^{-7}[d]	1.4×10^{-6}[e]	8.4×10^{-3}	3.4×10^{-4}	4.1×10^{-6}	1.9×10^{-5}
Mahi Mahi	3.56	1.10	3.92	6.0×10^{-4}[d]	2.4×10^{-5}[e]	3.0×10^{-7}[d]	1.4×10^{-6}[e]	2.1×10^{-3}	8.7×10^{-5}	1.1×10^{-6}	4.9×10^{-6}
Marine crabs[f]	1.68	0.90	1.51	3.3×10^{-4}	4.9×10^{-5}	3.6×10^{-5}	4.1×10^{-6}	5.5×10^{-4}	8.3×10^{-5}	6.0×10^{-5}	6.8×10^{-6}
Lobster[f]	3.88	0.90	3.49	3.3×10^{-4}	4.9×10^{-5}	3.6×10^{-5}	4.1×10^{-6}	1.3×10^{-3}	1.9×10^{-4}	1.4×10^{-4}	1.6×10^{-5}
Clams[c,d,g]	4.56	0.80	3.65	4.2×10^{-5}	1.3×10^{-4}	3.9×10^{-4}	1.2×10^{-4}	1.9×10^{-4}	6.0×10^{-4}	1.8×10^{-3}	5.4×10^{-4}
Trochus[c,d,g]	0.10	0.80	0.08	4.2×10^{-5}	1.3×10^{-4}	3.9×10^{-4}	1.2×10^{-4}	4.2×10^{-6}	1.3×10^{-5}	3.9×10^{-5}	1.2×10^{-5}
Tridacna muscle[c,d,g]	1.67	1.28	2.14	4.2×10^{-5}	1.3×10^{-4}	3.9×10^{-4}	1.2×10^{-4}	7.1×10^{-5}	2.2×10^{-4}	6.4×10^{-4}	2.0×10^{-4}
Jedrul[c,d,g]	3.08	0.80	2.46	4.2×10^{-5}	1.3×10^{-4}	3.9×10^{-4}	1.2×10^{-4}	1.3×10^{-4}	4.1×10^{-4}	1.2×10^{-3}	3.7×10^{-4}
Coconut crabs[c,h]	3.13	0.70	2.19	8.9×10^{-2}	3.9×10^{-2}	7.2×10^{-5}	2.3×10^{-5}	2.8×10^{-1}	1.2×10^{-1}	2.3×10^{-4}	7.2×10^{-5}
Land crabs[c,i]	0.00	0.70	0.00	8.9×10^{-2}	3.9×10^{-2}	7.2×10^{-5}	2.3×10^{-5}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Octopus	4.51	1.00	4.51	4.3×10^{-4}[j]	2.4×10^{-5}[e]	1.2×10^{-5}[e]	1.4×10^{-6}[e]	1.9×10^{-3}	1.1×10^{-4}	5.6×10^{-5}	6.2×10^{-6}
Turtle	4.34	0.89	3.86	6.6×10^{-5}[k]	2.4×10^{-5}[e]	1.2×10^{-5}[e]	1.4×10^{-6}[e]	2.9×10^{-4}	1.1×10^{-4}	5.4×10^{-5}	6.0×10^{-6}
Chicken muscle	8.36	1.70	14.2	1.3×10^{-1}[l]	1.3×10^{-4}[c]	2.5×10^{-6}[m]	3.3×10^{-6}[m]	1.1×10^{0}	1.1×10^{-3}	2.1×10^{-5}	2.8×10^{-5}
Chicken liver	4.50	1.64	7.38	8.8×10^{-2}[l]	2.9×10^{-4}[c]	1.5×10^{-5}[m]	3.1×10^{-5}[m]	4.0×10^{-1}	1.3×10^{-3}	6.8×10^{-5}	1.4×10^{-4}
Chicken gizzard	1.66	1.48	2.46	5.3×10^{-2}[c]	3.2×10^{-4}[c]	9.6×10^{-6}[m]	1.0×10^{-5}[m]	8.9×10^{-2}	5.3×10^{-4}	1.6×10^{-5}	1.7×10^{-5}
Pork muscle	5.67	4.50	25.5	4.9×10^{-1}[l]	9.0×10^{-5}[e]	1.3×10^{-6}[e]	9.1×10^{-7}[e]	2.8×10^{0}	5.1×10^{-4}	7.6×10^{-6}	5.2×10^{-6}
Pork kidney	NR	1.40	0.00	5.8×10^{-1}[l]	1.5×10^{-4}[c]	1.3×10^{-5}[m]	2.4×10^{-5}[m]	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Pork liver	2.60	2.41	6.27	2.0×10^{-1}[l]	1.5×10^{-4}[n]	3.4×10^{-5}[m]	1.3×10^{-5}[m]	5.3×10^{-1}	3.9×10^{-4}	8.8×10^{-5}	3.3×10^{-5}
Pork heart	0.31	1.95	0.61	5.1×10^{-1}[l]	9.0×10^{-5}[o]	1.3×10^{-6}[o]	9.1×10^{-7}[o]	1.6×10^{-1}	2.8×10^{-5}	4.1×10^{-7}	2.8×10^{-7}
Bird muscle[e]	2.71	1.70	4.61	6.7×10^{-4}	2.4×10^{-5}	1.2×10^{-5}	1.4×10^{-6}	1.8×10^{-3}	6.6×10^{-5}	3.4×10^{-5}	3.8×10^{-6}
Bird eggs	1.54	1.50	2.31	1.7×10^{-4}[p]	3.7×10^{-5}[p]	1.2×10^{-5}[e]	1.4×10^{-6}[e]	2.7×10^{-4}	5.7×10^{-5}	1.9×10^{-5}	2.1×10^{-6}
Chicken eggs[q]	7.25	1.63	11.8	1.3×10^{-1}	1.3×10^{-4}	2.5×10^{-6}	3.3×10^{-6}	9.4×10^{-1}	9.7×10^{-4}	1.8×10^{-5}	2.4×10^{-5}
Turtle eggs	9.36	1.50	14.0	6.6×10^{-5}[r]	2.4×10^{-5}[e]	1.2×10^{-5}[e]	1.4×10^{-6}[e]	6.2×10^{-4}	2.3×10^{-4}	1.2×10^{-4}	1.3×10^{-5}
Pandanus fruit[l]	8.66	0.60	5.20	2.5×10^{-1}	1.5×10^{-2}	1.6×10^{-6}	8.1×10^{-7}	2.1×10^{0}	1.3×10^{-1}	1.4×10^{-5}	7.0×10^{-6}
Pandanus nuts[s]	0.50	2.66	1.33	2.5×10^{-1}	1.5×10^{-2}	1.6×10^{-6}	8.1×10^{-7}	1.2×10^{-1}	7.3×10^{-3}	8.2×10^{-7}	4.0×10^{-7}
Breadfruit[l]	27.2	1.30	35.3	1.3×10^{-1}	2.0×10^{-3}	6.0×10^{-7}	7.4×10^{-7}	3.5×10^{0}	5.5×10^{-2}	1.6×10^{-5}	2.0×10^{-5}
Coconut juice[l]	99.1	0.11	10.9	3.2×10^{-2}	3.7×10^{-5}	9.8×10^{-7}	9.3×10^{-7}	3.2×10^{0}	3.6×10^{-3}	9.8×10^{-5}	9.2×10^{-5}
Coconut milk[l]	51.9	3.46	179	1.2×10^{-1}	5.2×10^{-4}	1.7×10^{-6}	2.1×10^{-6}	6.3×10^{0}	2.7×10^{-2}	8.6×10^{-5}	1.1×10^{-4}
Tuba/Jekero[l]	0.00	0.50	0.00	1.2×10^{-1}	5.2×10^{-4}	1.7×10^{-6}	2.1×10^{-6}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Drinking coco meat[l]	31.7	1.02	32.3	7.1×10^{-2}	3.3×10^{-4}	1.2×10^{-6}	1.4×10^{-6}	2.3×10^{0}	1.0×10^{-2}	3.9×10^{-5}	4.4×10^{-5}
Copra meat[l]	12.2	4.14	50.3	1.2×10^{-1}	5.2×10^{-4}	1.7×10^{-6}	2.1×10^{-6}	1.5×10^{0}	6.3×10^{-3}	2.0×10^{-5}	2.5×10^{-5}
Sprout. coco[l]	7.79	0.80	6.23	1.2×10^{-1}	5.2×10^{-4}	1.7×10^{-6}	2.1×10^{-6}	9.4×10^{-1}	4.0×10^{-3}	1.3×10^{-5}	1.6×10^{-5}
Marsh. cake[l]	11.7	3.36	39.2	1.2×10^{-1}	5.2×10^{-4}	1.7×10^{-6}	2.1×10^{-6}	1.4×10^{0}	6.0×10^{-3}	1.9×10^{-5}	2.4×10^{-5}
Papaya	6.59	0.39	2.57	4.3×10^{-1}[u]	6.7×10^{-3}[v]	4.7×10^{-6}[w]	4.9×10^{-6}[u]	2.8×10^{0}	4.4×10^{-2}	3.1×10^{-5}	3.2×10^{-5}
Squash	NR	0.47	0.00	2.1×10^{-1}[l]	2.8×10^{-3}[v]	6.3×10^{-7}[v]	6.5×10^{-7}[w]	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Pumpkin[x]	1.24	0.30	0.37	2.1×10^{-1}	2.8×10^{-3}	6.3×10^{-7}	6.5×10^{-7}	2.6×10^{-1}	3.5×10^{-3}	7.8×10^{-7}	8.1×10^{-7}
Banana	0.02	0.88	0.02	1.2×10^{-2}[l]	1.1×10^{-3}[u]	4.7×10^{-6}[y]	4.9×10^{-6}[y]	2.5×10^{-4}	2.3×10^{-5}	9.4×10^{-8}	9.8×10^{-8}
Arrowroot[l]	3.93	3.46	13.6	2.0×10^{-1}	2.5×10^{-3}	2.6×10^{-5}	1.3×10^{-5}	8.0×10^{-1}	1.0×10^{-2}	1.0×10^{-4}	5.2×10^{-5}
Citrus	0.10	0.49	0.05	5.7×10^{-2}[l]	2.0×10^{-3}[z]	6.0×10^{-7}[z]	7.4×10^{-7}[z]	5.7×10^{-3}	2.0×10^{-4}	6.0×10^{-8}	7.4×10^{-8}
Rainwater[aa]	313	0.00	0.00	1.2×10^{-5}	5.7×10^{-6}	1.1×10^{-7}	7.4×10^{-9}	3.6×10^{-3}	1.8×10^{-3}	3.5×10^{-5}	2.3×10^{-6}
Wellwater[aa]	207	0.00	0.00	2.6×10^{-5}	6.1×10^{-5}	4.7×10^{-7}	2.8×10^{-7}	5.5×10^{-3}	1.3×10^{-2}	9.8×10^{-5}	5.8×10^{-5}
Malolo[bb]	199	0.00	0.00	1.2×10^{-5}	5.7×10^{-6}	1.1×10^{-7}	7.4×10^{-9}	2.3×10^{-3}	1.1×10^{-3}	2.2×10^{-5}	1.5×10^{-6}
Coffee/Tea[bb]	228	0.00	0.00	1.2×10^{-5}	5.7×10^{-6}	1.1×10^{-7}	7.4×10^{-9}	2.6×10^{-3}	1.3×10^{-3}	2.5×10^{-5}	1.7×10^{-6}
Soil[l,cc,dd]	0.10	0.00	0.00	2.8×10^{-1}	1.6×10^{-1}	6.7×10^{-2}	5.1×10^{-2}	2.8×10^{-2}	1.6×10^{-2}	6.7×10^{-3}	5.1×10^{-3}
Total Local	1,322		547					31	0.47	0.012	0.0071
Fluids	1,046		11								
Solids	276		536								

Imported food	$g\,d^{-1}$	$kcal\,g^{-1}$ [a,b]	$kcal\,d^{-1}$
Baked bread	30.3	2.75	83.3
Fried bread	72.0	4.25	306
Pancakes	59.5	2.18	130
Cake	2.64	3.27	8.63
Rice	234	1.10	257
Instant mashed potatoes	127	0.90	114
Sugar	65.2	3.85	251
Canned chicken	13.0	1.98	25.7
Corned beef	78.7	2.16	170
Spam	55.0	2.28	125
Canned mackerel	44.0	1.83	80.5
Canned sardines	42.5	2.14	91.0
Canned tuna	59.0	1.98	117
Canned salmon	NR	2.03	0.00
Other canned fish	NR	2.00	0.00
Other meat, fish, or poultry	NR	2.00	0.00
Carbonated drinks	338	0.40	135
Orange juice	188	0.44	82.6
Tomato juice	99.5	0.19	18.9
Pineapple juice	178	0.55	97.6
Other canned juice	25.4	0.50	12.7
Evaporated milk	201	1.37	276
Powdered milk	72.9	1.37	99.9
Whole milk	0.00	0.68	0.00
Canned butter	0.00	7.16	0.00
Onion	0.00	0.45	0.00
Canned vegetables	NR	0.80	0.00
Baby food	NR	1.00	0.00
Cocoa	178	0.97	173
Ramen noodles	6.07	1.25	7.6
Candy	NR	4.00	0.00
Total Imported	2,168		2,661
Fluids	1,280		895
Solids	888		1,766
Total Local and Imported	3,490		3,208
Fluids	2,326		906
Solids	1,164		2,302

NOTE: NR stands for no response.
[a] Data from Murai et al. (1958).
[b] Includes data from Watt and Merrill (1963), Burton (1965), Buchanan (1947), and Pennington (1976).
[c] Specific activity from Robison et al. (1982).
[d] Specific activity from Noshkin et al. (1981a); Robison et al. (1981).
[e] Specific activity used is that of reef fish.
[f] Specific activity calculated using the ratio (Bq g^{-1} shellfish tissue wet weight vs. Bq g^{-1} fish tissue wet weight) from Bikini Atoll (Robison et al. 1988).
[g] Data used is from *Hippopus hippopus* and *Tridacna squamosa*.
[h] Data used is from coconut crabs from Arbar Island on Rongelap Atoll.
[i] Specific activity used is that of coconut crab.
[j] Specific activity calculated using the ratio (Bq g^{-1} octopus tissue wet weight vs. Bq g^{-1} fish tissue wet weight) from Bikini Atoll (Robison et al. 1988).
[k] Specific activity calculated using the ratio (Bq g^{-1} turtle tissue wet weight vs. Bq g^{-1} fish tissue wet weight) from Bikini Atoll (Robison et al. 1988).
[l] Specific activity is based on determinations from samples taken from Rongelap Island from the 1978 survey together with our most recent trips to Rongelap Island from 1986 through 1993.

[m] Specific activity is unpublished data from the 1978 NMIRS.
[n] Specific activity used is that of pork kidney.
[o] Specific activity used is that of pork muscle.
[p] Specific activity calculated using the ratio (Bq g^{-1} bird eggs wet weight vs. Bq g^{-1} bird muscle wet weight) from Bikini Atoll (Robison et al. 1988).
[q] Specific activity used is that of chicken muscle.
[r] Specific activity used is that of turtle.
[s] Specific activity used is that of *Pandanus* fruit.
[t] Specific activity used is that of copra meat. Tuba is made from the sap that normally would support coconut development.
[u] Specific activity used is calculated using concentration ratios (Bq g^{-1} fruit wet weight vs. Bq g^{-1} soil dry weight) from the other atolls taken on the 1978 survey.
[v] Specific activity used is calculated using concentration ratios (Bq g^{-1} fruit weight vs. Bq g^{-1} soil dry weight) from Bikini and Eneu Islands at Bikini Atoll.
[w] Specific activity used is calculated using the same concentration ratio for $^{239+240}Pu$ and ^{241}Am when no data is available and assuming $^{239+240}Pu$ and ^{241}Am are the same.
[x] Specific activity used is that of squash.
[y] Specific activity used is that of papaya.
[z] Specific activity used is that of breadfruit.
[aa] Specific activity from Noshkin et al. (1981b).
[bb] Specific activity used is that of rainwater.
[cc] Specific activity is in Bq g^{-1} dry weight.
[dd] Specific activity used is calculated using the time distribution of 16 h d^{-1} in the village area vs. 7 h d^{-1} in the interior of Rongelap Island.

model for the food intake rate (g d^{-1}) of local foods is the same for Utirik Island, and only the radioactivity intake rate (Bq d^{-1}) changes because of the lower concentration of ^{137}Cs in the soil and vegetation at Utirik relative to Rongelap. The basis of these diet models was the survey of the Ujelang community in 1978 by the Micronesian Legal Services Corporation (MLSC) staff and a Marshallese school teacher on Ujelang (Robison et al. 1980, 1987, 1994). The survey results were presented for adults (women and men), teenagers, and children. Adult intake exceeded that of teenagers and children, and the intake of local food was about 20% greater for women than for men. The higher intake attributed to women is unexplained and certainly questionable. It is indicative of the acknowledged uncertainty in dietary estimates. Nevertheless, we believe that the MLSC survey provides a reasonable basis for estimating the current dietary intake. Pending the availability of empirical data, we have chosen to use the higher (female) diet from the survey as our diet model rather than attempt further speculative refinement.

Detailed descriptions of LLNL dietary model and a review of other dietary data from the Marshall Islands are given by Robison et al. (1987, 1994). Also, these reports provide a detailed analysis of the caloric content of the diet model compared with United States and Japanese diets. The LLNL IA diet model (Table 1) has a daily calorie intake of about 3,208 calories, which is greater than the U.S. population average value, ranging from 1,853 calories to 1,925 calories (Yang and Nelson 1986; Abraham et al. 1979)

The idea that people will return to the historical lifestyle and consume only local foods without any imported foods continues to surface, although it is almost certain this type of lifestyle will not occur again in the Marshall Islands. Nonetheless, we have calculated the doses for such a diet scenario. The IUA diet data listed in Table 2 are those derived from the results of the Ujelang survey. However, as part of a National Academy of Sciences review in 1993 of the LLNL program, it was recommended that the calorie intake of the IUA diet as it came from the survey be doubled because the calorie intake was low and could not sustain a population for a long period of time (NRC 1994). We accomplished this by doubling the intake of all dietary items listed in Table 2. Consequently, the gram per day intake, the daily ^{137}Cs intake, and the calorie intake are double the values in Table 2 for the dose calculations for the local food only diet (IUA) and are reflected in the tables by the symbol IUA*2. Other diet models have been proposed by people associated with Marshall Islands projects and will be used for comparison (Naidu et al. 1980; Simon and Graham 1995).

The age-dependent biokinetic model for ^{137}Cs is that developed by Leggett (1986) and adopted by the *ICRP* (1990, 1991). It is a two compartment, exponential model with 10% of the ingested ^{137}Cs activity going to a short-term compartment with a biological half-life of 2 d and 90% going to a long-term compartment with a

Table 2. Diet model—Rongelap Island. Original imported foods unavailable (local foods only) diet for adults greater than 18 y.

Local food	$g\ d^{-1}$	$kcal\ g^{-1}$ [a,b]	$kcal\ d^{-1}$	Specific activity in 1995 ($Bq\ g^{-1}$ wet wt.) ^{137}Cs	^{90}Sr	$^{239+240}Pu$	^{241}Am	$Bq\ d^{-1}$ ^{137}Cs	^{90}Sr	$^{239+240}Pu$	^{241}Am
Reef fish[d]	43.4	1.40	60.7	6.7×10^{-4}	2.4×10^{-5}	1.2×10^{-5}	1.4×10^{-6}	2.9×10^{-2}	1.1×10^{-3}	5.4×10^{-4}	6.0×10^{-5}
Tuna	36.0	1.40	50.4	6.0×10^{-4d}	2.4×10^{-5e}	3.0×10^{-7d}	1.4×10^{-6e}	2.2×10^{-2}	8.8×10^{-4}	1.1×10^{-5}	5.0×10^{-5}
Mahi Mahi	10.7	1.10	11.8	6.0×10^{-4d}	2.4×10^{-5e}	3.0×10^{-7d}	1.4×10^{-6e}	6.5×10^{-3}	2.6×10^{-4}	3.2×10^{-6}	1.5×10^{-5}
Marine crabs[f]	9.75	0.90	8.78	3.3×10^{-4}	4.9×10^{-5}	3.6×10^{-5}	4.1×10^{-6}	3.2×10^{-3}	4.8×10^{-4}	3.5×10^{-4}	4.0×10^{-5}
Lobster[f]	17.6	0.90	15.8	3.3×10^{-4}	4.9×10^{-5}	3.6×10^{-5}	4.1×10^{-6}	5.7×10^{-3}	8.7×10^{-4}	6.3×10^{-4}	7.2×10^{-5}
Clams[c,d,g]	29.1	0.80	23.2	4.2×10^{-5}	1.3×10^{-4}	3.9×10^{-4}	1.2×10^{-4}	1.2×10^{-3}	3.8×10^{-3}	1.1×10^{-2}	3.4×10^{-3}
Trochus[c,d,g]	0.12	0.80	0.10	4.2×10^{-5}	1.3×10^{-4}	3.9×10^{-4}	1.2×10^{-4}	5.1×10^{-6}	1.6×10^{-5}	4.6×10^{-5}	1.4×10^{-5}
Tridacna muscle[c,d,g]	5.72	1.28	7.32	4.2×10^{-5}	1.3×10^{-4}	3.9×10^{-4}	1.2×10^{-4}	2.4×10^{-4}	7.6×10^{-4}	2.2×10^{-3}	6.8×10^{-4}
Jedrul[c,d,g]	9.69	0.90	8.72	4.2×10^{-5}	1.3×10^{-4}	3.9×10^{-4}	1.2×10^{-4}	4.1×10^{-4}	1.3×10^{-3}	3.7×10^{-3}	1.1×10^{-3}
Coconut crabs[c,h]	12.5	0.70	8.73	8.9×10^{-2}	3.9×10^{-2}	7.2×10^{-5}	2.3×10^{-5}	1.1×10^{0}	4.8×10^{-1}	9.0×10^{-4}	2.9×10^{-4}
Land crabs[c,i]	0.00	0.70	0.00	8.9×10^{-2}	3.9×10^{-2}	7.2×10^{-5}	2.3×10^{-5}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Octopus	24.5	1.00	24.5	4.3×10^{-4j}	2.4×10^{-5e}	1.2×10^{-5e}	1.4×10^{-6e}	1.1×10^{-2}	6.0×10^{-4}	3.1×10^{-4}	3.4×10^{-5}
Turtle	8.88	0.89	7.90	6.6×10^{-5k}	2.4×10^{-5e}	1.2×10^{-5e}	1.4×10^{-6e}	5.9×10^{-4}	2.2×10^{-4}	1.1×10^{-4}	1.2×10^{-5}
Chicken muscle	15.6	1.70	26.5	1.3×10^{-1l}	1.3×10^{-4e}	2.5×10^{-6m}	3.3×10^{-6m}	2.0×10^{0}	2.1×10^{-3}	3.9×10^{-5}	5.2×10^{-5}
Chicken liver	8.84	1.64	14.5	8.8×10^{-2l}	2.9×10^{-4e}	1.5×10^{-5m}	3.1×10^{-5m}	7.8×10^{-1}	2.5×10^{-3}	1.3×10^{-4}	2.7×10^{-4}
Chicken gizzard	1.66	1.48	2.46	5.3×10^{-2e}	3.2×10^{-4e}	9.6×10^{-6m}	1.0×10^{-5m}	8.9×10^{-2}	5.3×10^{-4}	1.6×10^{-5}	1.7×10^{-5}
Pork muscle	6.96	4.50	31.3	4.9×10^{-1l}	9.0×10^{-5e}	1.3×10^{-6e}	9.1×10^{-7e}	3.4×10^{0}	6.3×10^{-4}	9.3×10^{-6}	6.3×10^{-6}
Pork kidney	NR	1.40	0.00	5.8×10^{-1l}	1.5×10^{-4e}	1.3×10^{-5m}	2.4×10^{-5m}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Pork liver	3.35	2.41	8.07	2.0×10^{-1l}	1.5×10^{-4n}	3.4×10^{-5m}	1.3×10^{-5m}	6.8×10^{-1}	5.0×10^{-4}	1.1×10^{-4}	4.3×10^{-5}
Pork heart	0.31	1.95	0.61	5.1×10^{-1l}	9.0×10^{-5o}	1.3×10^{-6o}	9.1×10^{-7o}	1.6×10^{-1}	2.8×10^{-5}	4.1×10^{-7}	2.8×10^{-7}
Bird muscle[e]	13.2	1.70	22.4	6.7×10^{-4}	2.4×10^{-5}	1.2×10^{-5}	1.4×10^{-6}	8.8×10^{-3}	3.2×10^{-4}	1.6×10^{-4}	1.8×10^{-5}
Bird eggs	11.4	1.50	17.1	1.7×10^{-4p}	3.7×10^{-5p}	1.2×10^{-5e}	1.4×10^{-6e}	2.0×10^{-3}	4.2×10^{-4}	1.4×10^{-4}	1.6×10^{-5}
Chicken eggs[q]	20.6	1.63	33.6	1.3×10^{-1}	1.3×10^{-4}	2.5×10^{-6}	3.3×10^{-6}	2.7×10^{0}	2.7×10^{-3}	5.2×10^{-5}	6.8×10^{-5}
Turtle eggs	117	1.50	176	6.6×10^{-5r}	2.4×10^{-5e}	1.2×10^{-5e}	1.4×10^{-6e}	7.7×10^{-3}	2.9×10^{-3}	1.5×10^{-3}	1.6×10^{-4}
Pandanus fruit[l]	31.5	0.60	18.9	2.5×10^{-1}	1.5×10^{-2}	1.6×10^{-6}	8.1×10^{-7}	7.8×10^{0}	4.6×10^{-1}	5.1×10^{-5}	2.5×10^{-5}
Pandanus nuts[s]	1.00	2.66	2.66	2.5×10^{-1}	1.5×10^{-2}	1.6×10^{-6}	8.1×10^{-7}	2.5×10^{-1}	1.5×10^{-2}	1.6×10^{-6}	8.1×10^{-7}
Breadfruit[l]	93.1	1.30	121	1.3×10^{-1}	2.0×10^{-3}	6.0×10^{-7}	7.4×10^{-7}	1.2×10^{1}	1.9×10^{-1}	5.6×10^{-5}	6.9×10^{-5}
Coconut juice[l]	167	0.11	18.3	3.2×10^{-2}	3.6×10^{-5}	9.8×10^{-7}	9.3×10^{-7}	5.4×10^{0}	6.1×10^{-3}	1.6×10^{-4}	1.6×10^{-4}
Coconut milk[t]	60.9	3.46	211	1.2×10^{-1}	5.2×10^{-4}	1.7×10^{-6}	2.1×10^{-6}	7.4×10^{0}	3.2×10^{-2}	1.0×10^{-4}	1.2×10^{-4}
Tuba/Jekero[t]	0.00	0.50	0.00	1.2×10^{-1}	5.2×10^{-4}	1.7×10^{-6}	2.1×10^{-6}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Drinking coco meat[l]	90.4	1.02	92.2	7.1×10^{-2}	3.3×10^{-4}	1.2×10^{-6}	1.4×10^{-6}	6.4×10^{0}	3.0×10^{-2}	1.1×10^{-4}	1.3×10^{-4}
Copra meat[l]	35.7	4.14	148	1.2×10^{-1}	5.2×10^{-4}	1.7×10^{-6}	2.1×10^{-6}	4.3×10^{0}	1.8×10^{-2}	5.9×10^{-5}	7.3×10^{-5}
Sprout. coco[t]	61.2	0.80	48.9	1.2×10^{-1}	5.2×10^{-4}	1.7×10^{-6}	2.1×10^{-6}	7.4×10^{0}	3.2×10^{-2}	1.0×10^{-4}	1.3×10^{-4}
Marsh. cake[t]	0.00	0.76	0.00	1.2×10^{-1}	5.2×10^{-4}	1.7×10^{-6}	2.1×10^{-6}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Papaya	13.5	0.39	5.26	4.3×10^{-1u}	6.7×10^{-3v}	4.7×10^{-6w}	4.9×10^{-6u}	5.7×10^{0}	9.1×10^{-2}	6.3×10^{-5}	6.6×10^{-5}
Squash	NR	0.47	0.00	2.1×10^{-1l}	2.8×10^{-3x}	6.3×10^{-7x}	6.5×10^{-7w}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Pumpkin[x]	2.72	0.30	0.82	2.1×10^{-1}	2.8×10^{-3}	6.3×10^{-7}	6.5×10^{-7}	5.7×10^{-1}	7.7×10^{-3}	1.7×10^{-6}	1.8×10^{-6}
Banana	0.29	0.88	0.26	1.2×10^{-2l}	1.1×10^{-3u}	4.7×10^{-6y}	4.9×10^{-6y}	3.6×10^{-3}	3.3×10^{-4}	1.4×10^{-6}	1.4×10^{-6}
Arrowroot[l]	47.4	3.46	164	2.0×10^{-1}	2.5×10^{-3}	2.6×10^{-5}	1.3×10^{-5}	9.7×10^{0}	1.2×10^{-1}	1.2×10^{-3}	6.3×10^{-4}
Citrus	0.10	0.49	0.05	5.7×10^{-2}	2.0×10^{-3z}	6.0×10^{7z}	7.4×10^{-7z}	5.7×10^{-3}	2.0×10^{-4}	6.0×10^{-8}	7.4×10^{-8}
Rainwater[aa]	315	0.00	0.00	1.2×10^{-5}	5.7×10^{-6}	1.1×10^{-7}	7.4×10^{-9}	3.7×10^{-3}	1.8×10^{-3}	3.5×10^{-5}	2.3×10^{-6}
Wellwater[aa]	215	0.00	0.00	2.6×10^{-5}	6.1×10^{-5}	4.7×10^{-7}	2.8×10^{-7}	5.7×10^{-3}	1.3×10^{-2}	1.0×10^{-4}	6.0×10^{-5}
Malolo[bb]	0.00	0.00	0.00	1.2×10^{-5}	5.7×10^{-6}	1.1×10^{-7}	7.4×10^{-9}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Coffee/Tea[bb]	0.00	0.00	0.00	1.2×10^{-5}	5.7×10^{-6}	1.1×10^{-7}	7.4×10^{-9}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}	0.0×10^{0}
Soil[l,cc,dd]	0.10	0.00	0.00	2.8×10^{-1}	1.6×10^{-1}	6.7×10^{-2}	5.1×10^{-2}	2.8×10^{-2}	1.6×10^{-2}	6.7×10^{-3}	5.1×10^{-3}
Total Local	1,541		1,392					78	1.5	0.031	0.013
Fluids	696		18								
Solids	845		1,374								

NOTE: NR stands for no response.
[a] Data from Murai et al. (1958).
[b] Includes data from Watt and Merrill (1963), Burton (1965), Buchanan (1947), and Pennington (1976).
[c] Specific activity from Robison et al. (1982).
[d] Specific activity from Noshkin et al. (1981a); Robison et al. (1981).
[e] Specific activity used is that of reef fish.
[f] Specific activity calculated using the ratio (Bq g^{-1} shellfish tissue wet weight vs. Bq g^{-1} fish tissue wet weight) from Bikini Atoll (Robison et al. 1988).
[g] Data used is from *Hippopus hippopus* and *Tridacna squamosa*.
[h] Data used is from coconut crabs from Arbar Island on Rongelap Atoll.
[i] Specific activity used is that of coconut crab.
[j] Specific activity calculated using the ratio (Bq g^{-1} octopus tissue wet weight vs. Bq g^{-1} fish tissue wet weight) from Bikini Atoll (Robison et al. 1988).
[k] Specific activity calculated using the ratio (Bq g^{-1} turtle tissue wet weight vs. Bq g^{-1} fish tissue wet weight) from Bikini Atoll (Robison et al. 1988).
[l] Specific activity is based on determinations from samples taken from Rongelap Island from the 1978 survey together with our most recent trips to Rongelap Island from 1986 through 1993.
[m] Specific activity is unpublished data from the 1978 NMIRS.
[n] Specific activity used is that of pork kidney.
[o] Specific activity used is that of pork muscle.
[p] Specific activity calculated using the ratio (Bq g^{-1} bird eggs wet weight vs. Bq g^{-1} bird muscle wet weight) from Bikini Atoll (Robison et al. 1988).
[q] Specific activity used is that of chicken muscle.
[r] Specific activity used is that of turtle.
[s] Specific activity used is that of *Pandanus* fruit.
[t] Specific activity used is that of copra meat.
[u] Specific activity used is calculated using concentration ratios (Bq g^{-1} fruit wet weight vs. Bq g^{-1} soil dry weight) from the other atolls taken on the 1978 survey.
[v] Specific activity used is calculated using concentration ratios (Bq g^{-1} fruit weight vs. Bq g^{-1} soil dry weight) from Bikini and Eneu Islands at Bikini Atoll.
[w] Specific activity used is calculated using the same concentration ratio for $^{239+240}$Pu and ^{241}Am when no data is available and assuming $^{239+240}$Pu and ^{241}Am are the same.
[x] Specific activity used is that of squash.
[y] Specific activity used is that of papaya.
[z] Specific activity used is that of breadfruit.
[aa] Specific activity from Noshkin et al. (1981b).
[bb] Specific activity used is that of rainwater.
[cc] Specific activity is in Bq g^{-1} dry weight.
[dd] Specific activity used is calculated using the time distribution of 16 h d^{-1} in the village area vs. 7 h d^{-1} in the interior of Rongelap Island.

biological half-life of 110 d. Data from BNL support the use of the 110 d half-life for the average adult males in the Marshall Islands (Miltenberger et al. 1980, 1981; Lessard et al. 1980a, 1980b, 1984).

In this paper we calculate the average ^{137}Cs body burden only for the adult age group. The estimated dose from ^{137}Cs for adults is a conservative estimate of dose for intake beginning at any other age based on available age-specific dietary information from the Marshall Islands (Robison and Phillips 1989).

Whole body counting system and radiocesium measurements

In vivo WBC is a simple, accurate, and effective method to determine the quantity of gamma emitters in the body, such as ^{40}K, ^{60}Co and ^{137}Cs. Hence, the WBC is an important technique employed in assessing the internally deposited radionuclides in the Marshallese populations since 1957 (Conard 1992). The WBC measurements have been conducted by scientists at BNL (Greenhouse et al. 1980) over the past 20 y; many of the body burden measurements for the Marshallese using the WBC and urinalyses methods are available (Cohn et al. 1956, 1963; Cohn and Gusmano 1965; Greenhouse et al. 1980; Miltenberger et al. 1980, 1981; Lessard et al. 1980a, 1980b, 1984; Sun et al. 1991, 1992).

Whole-body counting was performed in two shadow-shielded chairs, each having a single thallium-doped sodium iodide detector, 20.2 cm (11.5 inches) diameter by 10.2 cm (4 inches) thick, produced by Bicron.[‡] The WBC detector is mounted on a pivoted arm allowing it to be centered across the front of the chair where the people are seated for 15 min during a counting. The WBC system is calibrated with a bottle mannequin absorber (BOMAB) phantom. Isotope identifications are based on four distinct photon energy peaks: 0.622 (^{137}Cs), 1.17 and 1.33 (^{60}Co), and 1.46 MeV (^{40}K). Counting efficiencies are established for four geometries by selecting whole or partial sets of the BOMAB phantom's segments called large, medium, small, and infant. The counting efficiency obtained with the large geometry is used to analyze spectra from persons weighing 60 kg or more, the medium geometry for persons weighing between 40 and 60 kg, the small geometry for youngsters age 3 y or older who weigh less than 40 kg, and the smallest geometry for infants less than about 14 kg. The minimum detectable activities (MDA) of ^{137}Cs and ^{60}Co at the 95% confidence level for an empty chair for the present WBC system are 60 and 52 Bq, respectively (NCRP 1985; Sun et al. 1991).

All measurements were made on volunteers from among the Marshallese who were residing on either Rongelap or Utirik Atolls. It was assumed that measured cesium activity is maintained in the body over 365 d as the result of a series of chronic intakes. Cesium body burdens in Marshallese must be interpreted on the basis of chronic intakes (Lessard et al. 1980a; Sun et al. 1991; Kercher and Robison 1993).

[‡] Bicron, 6801 Cochran Road, Solon, OH 44139.

RESULTS AND DISCUSSION

The initial ^{137}Cs intake (kBq mo^{-1}) in 1974 for the various diet models is listed in Table 3. The estimated body burdens based on the environmental method for the years 1977 through 1984 for Rongelap and 1977 through 1993 for Utirik are listed in Table 4 for the various diet models. The body burdens were calculated using the data from food samples collected on Rongelap and Utirik Islands from 1978 through 1993. The data were decay corrected to 1970 to serve as input to the dose model. The body burdens were calculated for a 25 y period (1970 to 1995), and the body burdens were extracted for the appropriate year for comparison with the BNL whole body measurements.

The BNL body burden data for ^{137}Cs in the adult population at both atolls are shown in Table 5. These data represent the mean body burden of the adults (both male and female) who volunteered to be measured on any given trip. The number of people varied each year, as did the actual persons involved. Also listed are the upper 95% confidence limits for the mean body burdens observed on each trip. The 95% confidence limits for each set of BNL body burden measurements for a specific year and island were calculated as follows. The lower bound (LB) = the 2.5th percentile of the data values if $n > 39$, otherwise LB = the minimum data value. The upper bound (UB) = the 97.5th percentile of the data values if $n > 39$, otherwise UB = the maximum data value. The minimum or maximum data values are used when $n < 39$ because the LB and UB cannot be calculated for such a case (i.e., $0.025 \times 39 = 0.98$; less than one individual.

Several other diet models have been suggested for the Marshall Islands for use in dose calculations (Naidu et al. 1980; Simon and Graham 1995). The original reports can be reviewed for detailed intakes of each food product. Rather than list three more very extensive tables, the body burdens calculated using these diets are shown in Figs. 6 and 7, along with the results from the LLNL preferred diet model (IA) and the local foods only diet model (IUA) as described in Tables 1 and 2. For a variety of reasons, politicians, lawyers, some community members, and others have insisted that a diet consisting of consumption of only locally grown foods should be used for dose calculations.

The very good agreement between the estimated ^{137}Cs body burdens from the LLNL environmental

Table 3. The initial intake in 1974 in kBq per month for the various diet models for Rongelap and Utirik Islands

	^{137}Cs intake, kBq mo^{-1}	
	Rongelap Island	Utirik Island
IA	1.54	0.316
IUA*2[a]	7.62	1.43
Naidu A	13.2	2.94
Naidu B	4.37	0.957
Naidu C	4.11	0.918

[a] IUA*2 represent a doubling of the values listed in the original IUA (local food only) diet listed in Table 2 (see text for explanation).

Table 4. The estimated body burdens in kBq for the populations at Rongelap and Utirik Atolls by the environmental method for various diet models.

	^{137}Cs body burden, kBq					
	Utirik Island					
Diet model	1977	1979	1981	1982	1983	1984
IA	1.41	1.35	1.29	1.26	1.23	1.20
IUA*2[a]	6.22	5.94	5.68	5.55	5.43	5.31
Naidu A	12.8	12.2	11.7	11.4	11.1	10.9
Naidu B	4.16	3.98	3.81	3.72	3.63	3.54
	Rongelap Island					
Diet model	1977	1979	1981	1982	1983	1984
IA	6.89	6.59	6.29	6.15	6.01	5.87
IUA*2[a]	33.1	31.6	30.3	29.5	28.9	28.3
Naidu A	57.4	54.8	52.4	51.3	50.1	48.9
Naidu B	19.0	18.2	17.4	16.9	16.6	16.2

[a] IUA*2 represent a doubling of the values listed in the original IUA (local food only) diet listed in Table 2 (see text for explanation).

Table 5. The BNL mean whole body measurements in kBq for populations at Rongelap and Utirik Islands for 1977 through 1993.

	Body Burdens, kBq								
	1977	1979	1981	1982	1983	1984	1989	1991	1993
Rongelap									
Mean	9.3	6.3	6.8	9.2	8.3	3.7			
Upper 95% confidence	18.5	17.0	17.4	13.0	20.8	11.2			
	(51)[a]	(35)	(66)	(47)	(52)	(78)			
Utirik									
Mean	3.8	2.0	3.1	—	2.1	1.0	0.8	1.1	0.4
Upper 95% confidence	7.4	3.7	6.9		4.4	2.6	3.0	2.9	1.5
	(48)	(36)	(126)	—	(168)	(165)	(143)	(153)	(103)

[a] Number in parentheses is the number of people measured.

method using the preferred diet model (IA) and the BNL whole body counting method provide a basis for evaluating proposed diet models in the Marshall Islands. As can be seen in Fig. 6, the LLNL diet model that provides for both local foods and imported foods in the diet reflects very well the results observed in the whole body counting of the people at Rongelap Island over a 7-y period. The IUA scenario, and other proposed diet models, significantly over predict actual observation by WBC at Rongelap Island.

The results from Utirik Atoll (Fig. 7) span a range of 16 y (1977 to 1993) and provide a slightly different picture of dietary intake in the years from 1977 to 1983. In 1977 to 1981 and 1982 the intake of local foods was significantly higher than predicted by the LLNL IA diet model. In 1979 and 1983, the whole body measurements indicate that the local food intake was slightly above model predictions. From 1984 through 1993, the environmental method and WBC are in excellent agreement as was the case for Rongelap Atoll. The higher intake of local foods at Utirik Atoll relative to Rongelap Atoll from 1977 through 1983 could reflect the more constant supply of imported foods from the U.S. to Rongelap Atoll via the Trust Territory and Republic of the Marshall Islands Government (RMI) because of the higher level of contamination at Rongelap. When the air strips were established on the outer atolls in the early 1980's, service

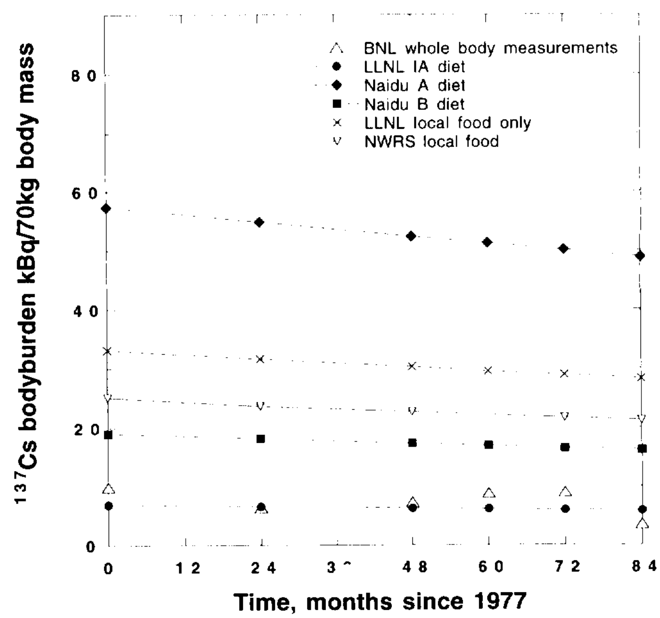

Fig. 6. The estimated body burdens for Rongelap Island for various diet models from the environmental method compared with the WBC method.

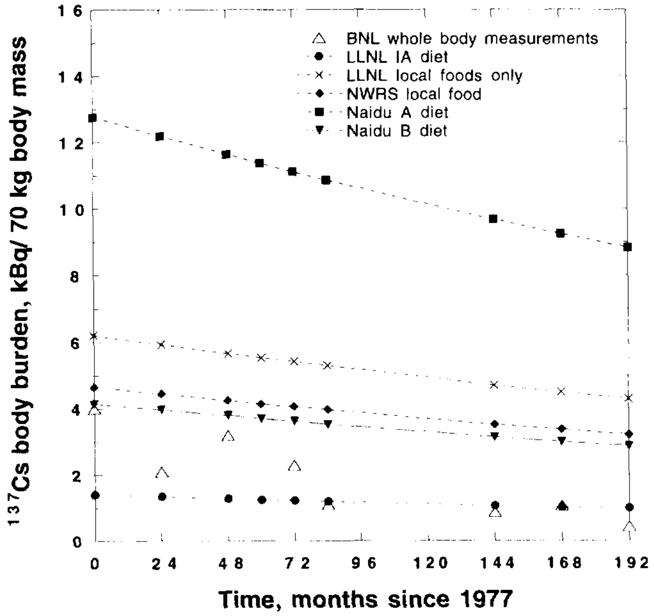

Fig. 7. The estimated body burdens for Utirik Island for various diet models from the environmental method compared with the WBC method.

became much more regular and imported foods could be delivered routinely to nearly all outer atolls. Ship service to the outer atolls has also improved under the RMI. Consequently, the combined diet of local and imported is obviously the preferred, and now standard, diet of the northern Marshall Island atolls, and the measured body burdens over the past 10 y are in excellent agreement with model predictions at both atolls.

General observation of the lifestyle in the Marshall Islands, with weekly airplane service, boat support periodically, trade with the outside world, government programs to ensure availability of imported foods, and a population that now enjoys and expects imported foods, indicates that the average diet in the Marshall Islands will more closely resemble the combined diet of imported and local foods than a diet of only local foods or other suggested diet models. This is particularly true for the most affected atolls of Bikini, Enewetak, Rongelap and Utirik, two for which we have direct data, and the other two which have very similar lifestyles to the other two atolls.

Resettlement of the atolls in order to live at "home" is very important to many of the people. The fact that the people are not currently living on the atolls precludes any direct whole body measurements. Consequently, decisions on resettlement are made based on dose estimates from the environmental method. Therefore, realistic dose assessments should be made so that people are not excluded *a priori* from going home because of unrealistic, over-conservative dose calculations. In the Marshall Islands, this necessarily translates into realistic diet models for estimating the intake of local foods because of the importance of ^{137}Cs uptake into terrestrial foods that subsequently provides a majority of the estimated dose. It is very clear from the comparative data shown in Figs. 6 and 7 that proposed diets consisting of consumption of only locally grown food stuffs simply do not represent the current diet in the Marshall Islands. This is very evident at both Rongelap and Utirik Atolls. The same is also true for the other diet models that have been proposed that are shown in Figs. 6 and 7. Consequently, based on these direct comparative data at two atolls, and general observations on current dietary habits in the Marshall Islands, a combined diet of imported and local foods should be used to provide realistic dose assessments.

Another very important part of any dose assessment is the uncertainty that surrounds the population average values. A detailed uncertainty analysis of these environmental-method dose estimates (i.e., body burdens) has been made for Rongelap Island (Robison et al. 1994). The method can be reviewed in the associated paper in this issue that describes the uncertainty analysis methods for the Bikini Island dose assessment (Bogen et al. 1997).

The results of the uncertainty analysis for the environmental method are shown in Fig. 8 where the upper 95% confidence limits for individual variability in the population average dose are shown by the solid circles connected by a solid line. For comparison, 95% confidence limits based on directly measured body burdens from BNL for each year at Rongelap and Utirik Atolls are shown by open diamonds for Rongelap and by open triangles for Utirik.

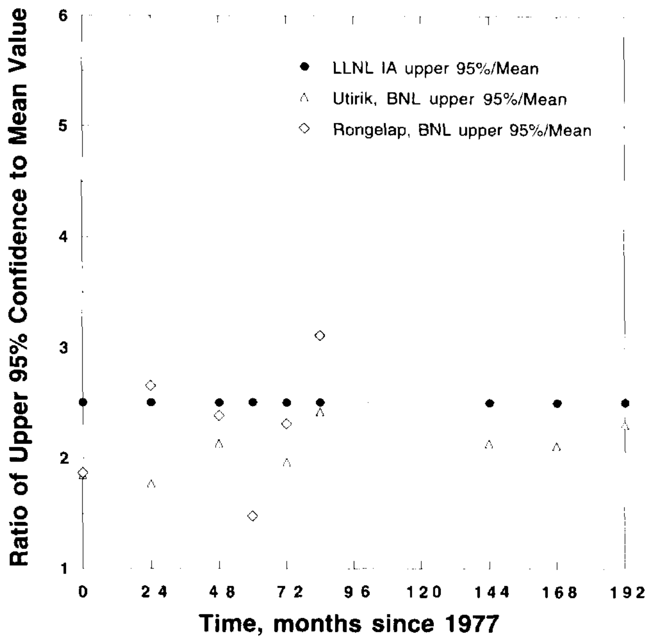

Fig. 8. The comparison of the 95% confidence limits for interindividual variabiltiy from the environmental method with the 95% confidence limits from experimental data by WBC for both Rongelap and Utirik Islands.

The upper 95% confidence limits from the direct measurement of both populations for all the years are within the modeled upper 95% confidence limits with the one exception in 1984 (84 mo. since 1977) at Rongelap. The model estimates of the interindividual variability around the population's mean predict very well actual observations and thus provide assurance about the environmental dose estimates and interindividual variability when applied to other atolls and islands.

Moreover, the modeled 95% confidence limits in uncertainty in the population average dose are a factor of 2 above and below the calculated mean value. The upper 95% confidence limits based on the population average observed by BNL at the two atolls over the years are 1.6 for Rongelap and 2.1 for Utirik, a result once again in good agreement with the environmental method uncertainty of 2.0. This provides additional confidence in applying the predictive LLNL environmental method to other atolls and islands where people do not currently reside, but where resettlement is likely or assumed.

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